

QCD Exotics

Stephen Lars Olsen¹

¹*Seoul National University, Seoul*

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QCD-motivated models for hadrons predict an assortment of “exotic” hadrons that have structures that are more complex than the quark-antiquark mesons and three-quark baryons of the original quark-parton model. These include pentaquark baryons, the six-quark H -dibaryon, and tetra-quark, hybrid, and glueball mesons. Despite extensive experimental searches, no unambiguous candidates for any of these exotic configurations have yet to be identified. On the other hand, a number of meson states, one that seems to be a proton-antiproton bound state, and others that contain either charmed-anticharmed quark pairs or bottom-antibottom quark pairs, have been recently discovered that neither fit into the quark-antiquark meson picture nor match the expected properties of the QCD-inspired exotics. Here I briefly review results from a recent search for the H -dibaryon, and discuss some properties of the newly discovered states –the so-called XYZ mesons– and compare them with expectations for conventional quark-antiquark mesons and the predicted QCD-exotic states.

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INTRODUCTION

The strongly interacting particles of the Standard Model (SM) are colored quarks and gluons, the strongly interacting particles in nature are color-singlet mesons and baryons. In the SM, quarks and gluons are related to mesons and baryons by the long-distance regime of QCD, which remains the least understood aspect of the theory. Since first-principle lattice-QCD (LQCD) calculations are still not practical for most long-distance phenomena, a number of models motivated by the color structure of QCD have been proposed. However, so far at least, predictions of these QCD-motivated models that pertain to the spectrum of hadrons have not had great success.

For example, it is well known that combining a quark triplet with an antiquark antitriplet gives the familiar meson octet of flavor- $SU(3)$. Using similar considerations based on QCD, two quark triplets can be combined to form a “diquark” antitriplet and a sextet as illustrated in Fig. 1a. In QCD, these diquarks will have color: combining a red triplet with a blue triplet – as shown in the figure – produces a magenta (anti-green) diquark and for the antitriplet combination, which is antisymmetric in color space, the color force between the two quarks is expected to be attractive. Likewise, green-red and blue-green diquarks form yellow (antiblue) and cyan (antired) antitriplets as shown in Fig. 1b.

Since these diquarks are not color-singlets, they cannot exist as free particles but, on the other hand, the anticolored diquark antitriplets should be able to combine with other colored objects in a manner similar to antiquark antitriplets, thereby forming multi-quark color-singlet states with more a complex substructure than the $q\bar{q}$ mesons and qqq baryons of the original quark model. These so-called “exotic” states include pentaquark baryons, H -dibaryons and tetraquark mesons, and are illustrated in Fig. 1c. Other proposed exotic states are glueballs, which are mesons made only from gluons, hybrids formed from a q , \bar{q} and a gluon, and deuteron-like bound states of color-singlet “normal” hadrons, commonly referred to as molecules. These are illustrated in Fig. 1d. Glueball and hybrid mesons are motivated by QCD; molecules are a generalization of classical nuclear physics to systems of subatomic particles.

PENTAQUARKS AND H -DIBARYONS

All of the above-mentioned candidates for exotic states have been the subject of numerous theoretical and experimental investigations during the four decades that have elapsed since QCD was first formulated. This activity peaked in 2003 when the LEPS experiment at the SPRING-8 electron ring in Japan reported the observation of a peak in the K^+n invariant mass distribution in $\gamma n \rightarrow K^+K^-$ reactions on a carbon target [1], with properties close to those that had been predicted for the $S = +1$ Θ_5^+ pentaquark [2]. This created a lot of excitement at the time [3] but subsequent, high-statistics experiments [4] gave negative results. The current “common wisdom” is that pentaquarks do not exist [5], or at least have yet to be found.

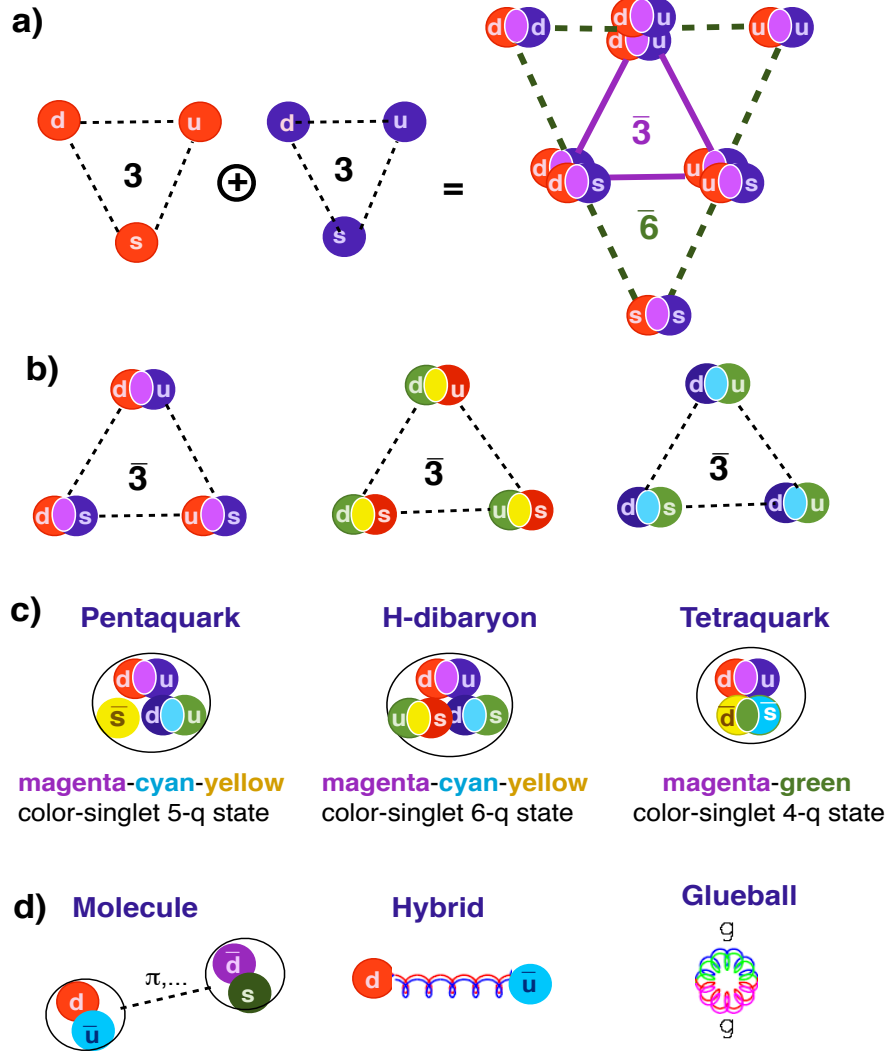


FIG. 1: **a)** Combining a red and blue quark triplet produces a magenta (antigreen) antitriplet and a sextet. The antitriplet contains antisymmetric qq combinations, the sextet has all symmetric combinations. **b)** The three anticolored diquark antitriplets. **c)** Some of the multiquark, color-singlet states that can be formed from quarks, antiquarks, diquarks and diantiquarks. **d)** Other possible non- $q\bar{q}$ meson systems.

The H -dibaryon was predicted by Jaffe in 1977 to be a doubly strange, tightly bound six-quark structure ($uuddss$) with isospin zero and $J^P = 0^+$ [6]. An $S = -2$ state with baryon number $B = 2$ and mass below $2m_\Lambda$ could only decay via weak interactions and, thus, would be long-lived. Although Jaffe's original prediction that the H would be ~ 80 MeV below the $2m_\Lambda$ threshold was ruled out by the observation of double- Λ hypernuclei, most notably the famous “Nagara” event [7] that limited the allowed H region to masses above $2m_\Lambda - 7.7$ MeV, the theoretical case for an H -dibaryon with mass near $2m_\Lambda$ continues to be strong, and has been recently strengthened by two independent LQCD calculations, both of which find an H -dibaryon state with mass near $2m_\Lambda$ [8].

Belle H -dibaryon search

The Belle experiment recently reported results of a search for production of an H -dibaryon with mass near $2m_\Lambda$ in inclusive $\Upsilon(1S)$ and $\Upsilon(2S)$ decays [9]. Decays of narrow $\Upsilon(nS)$ ($n = 1, 2, 3$) bottomonium ($b\bar{b}$) resonances are particularly well suited for searches for multiquark states with non-zero strangeness. The $\Upsilon(nS)$ states are flavor-

$SU(3)$ singlets that primarily decay via annihilation into three gluons. The gluons materialize into $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs with nearly equal probabilities, creating final states with a high density of quarks and antiquarks in a limited volume of phase space. A benchmark for the rate for multi-quark-state production in these decays is the measured inclusive decay branching fractions to antideuterons \bar{D} : $\mathcal{B}(\Upsilon(1S) \rightarrow \bar{D} + X) = (2.9 \pm 0.3) \times 10^{-5}$ and $\mathcal{B}(\Upsilon(2S) \rightarrow \bar{D} + X) = (3.4 \pm 0.6) \times 10^{-5}$ [10]. If the six-quark H -dibaryon is produced at a rate that is similar to that for six-quark antideuterons, there should be many thousands of them in the 102 million $\Upsilon(1S)$ and 158 million $\Upsilon(2S)$ event samples collected by Belle.

For H masses below $2m_\Lambda$, Belle searched for $H \rightarrow \Lambda p \pi^-$ (& $\bar{H} \rightarrow \bar{\Lambda} \bar{p} \pi^+$) signals in the inclusive $\Lambda p \pi^-$ invariant mass distribution [29]. For masses above $2m_\Lambda$, the $H \rightarrow \Lambda \Lambda$ (& $\bar{H} \rightarrow \bar{\Lambda} \bar{\Lambda}$) mode was used. Figure 2 shows the measured $\Lambda p \pi^-$ (left) & $\bar{\Lambda} \bar{p} \pi^+$ (center-left) invariant mass spectra for masses below $2m_\Lambda$ and the $\Lambda \Lambda$ (center-right) and $\bar{\Lambda} \bar{\Lambda}$ (right) mass spectra for masses above $2m_\Lambda$. Here results from the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples are combined. No signal is observed. The solid red curves show results of a background-only fit to the data; the dashed curve shows the MC expectations for an H -dibaryon produced at 1/20th of the antideuteron rate. Upper limits on the inclusive branching ratios that are at least a factor of twenty below that for antideuterons are set over the entire $|M_H - 2m_\Lambda| < 30$ MeV mass interval.

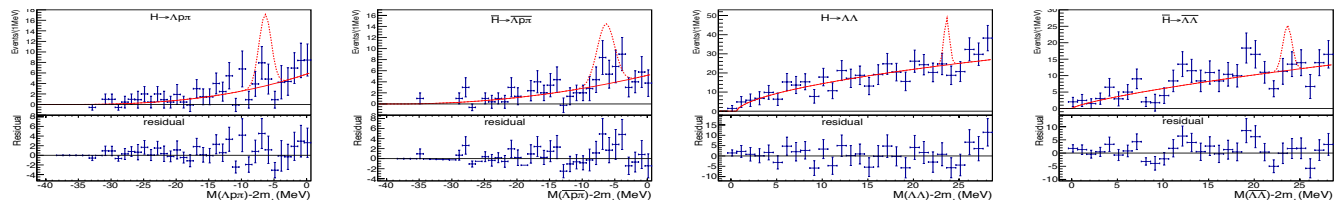


FIG. 2: The $\Lambda p \pi^-$, $\bar{\Lambda} \bar{p} \pi^+$, $\Lambda \Lambda$ and $\bar{\Lambda} \bar{\Lambda}$ invariant mass distributions (from left to right). The solid curves show results of background-only fits and the lower panels show the fit residuals. The dashed curves are expected signals for an H production rate that is 1/20th that for \bar{D} 's.

Neither pentaquarks nor the H -dibaryon are seen in spite of the strong theoretical motivation for their existence. The absence of pentaquarks led Wilczek to remark “*The story of the pentaquark shows how poorly we understand QCD*” [11]. The absence of any evidence for the H -dibaryon (among other things) led Jaffe to observe that “*The absence of exotics is one of the most obvious features of QCD*” [12].

WHAT WE DO SEE

Although forty years of experimental searches has failed to come up with compelling evidence for specifically QCD-motivated exotic hadrons, strong evidence for mesons that do not fit into the simple $q\bar{q}$ scheme of the original quark model has been steadily accumulating during the past decade. These include a candidate for a bound state of a proton and antiproton from the BESII experiment [13] – so-called “baryonium” – which is an idea that has been around for a long, long time [15], and the XYZ mesons, which are charmonium-like and bottomonium-like states that do not fit into any of the remaining unfilled states in the $c\bar{c}$ - and $b\bar{b}$ -meson level schemes [16].

Baryonium in radiative $J/\psi \rightarrow \gamma p \bar{p}$ decays?

In 2003, the BESII experiment reported the observation of a strong near-threshold mass enhancement in the $p\bar{p}$ invariant mass spectrum in radiative $J/\psi \rightarrow \gamma p \bar{p}$ decays, shown in the top-left panel of Fig. 3 [13]. The lower panel in the figure shows how the $M(p\bar{p})$ spectrum looks when the effects of phase-space are divided out (assuming an S -wave $p\bar{p}$ system). It seems apparent from the phase-space-corrected plot that the dynamical source for this enhancement, whatever it may be, is at or below the mass threshold. A fit with a Breit-Wigner (BW) line shape modified by a kinematic threshold factor yielded a peak mass of 1859^{+6}_{-27} MeV and width $\Gamma < 30$ MeV [14]. It was subsequently pointed out that the BW form used by BESII should be modified to include the effect of final-state-interactions on the shape of the $p\bar{p}$ mass spectrum [17]. When this is done, the peak mass shifts downward, from 1859 MeV to 1831 ± 7 MeV and the range of allowed widths increases to $\Gamma < 153$ MeV.

Soon after the BESII publication, Yan and Ding proposed a Skyrme-like model for proton-antiproton interactions in which BESII's $p\bar{p}$ mass-threshold enhancement is an S -wave $p\bar{p}$ bound state with binding energy around 20 MeV [18].

Since the p and the \bar{p} in such a system would annihilate whenever they came within close proximity of each other, such a state would have a finite width, creating a situation illustrated by the cartoon in the center-left panel of Fig. 3: for masses above the $2m_p$ threshold, the state would decay essentially 100% of the time by “falling apart” into a p and \bar{p} ; for masses below $2m_p$, the decay would proceed via $p\bar{p}$ annihilation. Since a preferred channel for low-energy S -wave $p\bar{p}$ annihilation is $\pi^+\pi^-\eta'$, Yan and Ding advocated a search for subthreshold decays of this same state in radiative $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decays. A subsequent BESII study of $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decays found a distinct peak at 1834 ± 7 MeV and width 68 ± 21 MeV as shown in the center-right panel of Fig. 3 [19], in good agreement with the mass and width results from the FSI-corrected fit to the $p\bar{p}$ mass spectrum.

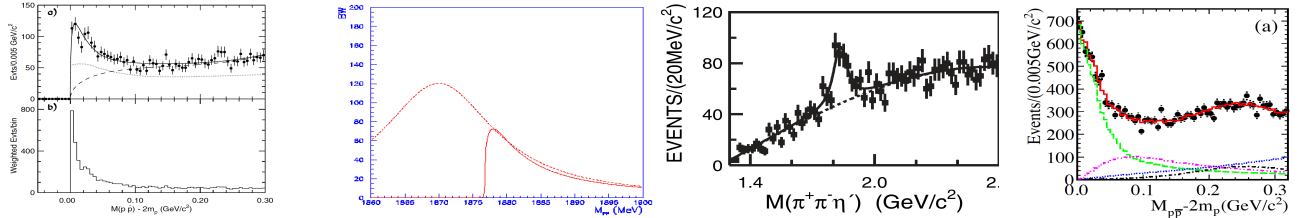


FIG. 3: **Left)** The upper panel shows the $M(p\bar{p})$ distribution for $J/\psi \rightarrow \gamma p\bar{p}$ decays from BESII [13]. The lower panel shows the same distribution with the kinematic threshold suppression factor removed. **Center-left)** A cartoon showing a BW line shape and a threshold-attenuated BW line-shape for a hypothesized baryonium state. The solid curve shows the expected $p\bar{p}$ line shape. Below threshold, where the dashed curve dominates, the state decays via $p\bar{p}$ annihilation. **Center-right)** The $M(\pi^+\pi^-\eta')$ mass distribution for $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ decays from ref. [19]. **Right)** The $M(p\bar{p})$ distribution for $J/\psi \rightarrow \gamma p\bar{p}$ from BESIII [20] with PWA results shown as histograms.

However, the situation still remains unclear. The $p\bar{p}$ mass-threshold enhancement was confirmed at the same mass with much higher statistics by BESIII [20], now with a significance that is $> 30\sigma$ (see the right panel of Fig. 3). The large BESIII event sample permitted the application of a partial wave analysis (PWA) that established the $J^{PC} = 0^{-+}$ quantum number assignment, in agreement with baryonium expectations. The $M(\pi^+\pi^-\eta')$ peak in $J/\psi \rightarrow \pi^+\pi^-\eta'$ decays was also confirmed and the production angle distribution was found to be consistent with a $J^{PC} = 0^{-+}$ assignment. But the new result finds a much larger width than that found for the $p\bar{p}$ peak in the BESIII partial wave analysis: $\Gamma_{\pi^+\pi^-\eta'} = 190 \pm 38$ MeV versus the $\Gamma_{p\bar{p}} < 76$ MeV upper limit from the BESIII PWA. Another puzzling feature is the lack of any evidence for the $p\bar{p}$ threshold enhancement in any other channels, such as $J/\psi \rightarrow \omega p\bar{p}$ [22], $\Upsilon(1S) \rightarrow \gamma p\bar{p}$ [23] or in B decays [24]. BESIII is actively looking at various other radiative J/ψ decay channels for evidence for or against a resonance near 1835 MeV [25].

The XYZ mesons

The XYZ mesons are a class of hadrons that are seen to decay to final states that contain a heavy quark and a heavy antiquark (i.e., Q and \bar{Q} , where Q is either a c or b quark), but cannot be easily accommodated in an unfilled $Q\bar{Q}$ level. Since the c and b quarks are heavy, their production from the vacuum in the fragmentation process is heavily suppressed. Thus, heavy quarks that are seen among the decay products of a hadron must have existed among its original constituents. In addition, the heavy quarks in conventional $Q\bar{Q}$ “quarkonium” mesons are slow and can be described reasonably well by non-relativistic Quantum Mechanics. Indeed it was the success of the charmonium model description of the ψ and χ_c states in the mid-1970’s that led to the general acceptance of the reality of quarks and the validity of the quark model. The Quarkonium model specifies the allowed states of a $Q\bar{Q}$ system; if a meson decays to a final state with a Q and a \bar{Q} and does not match the expected properties of any of the unfilled levels in the associated quarkonium spectrum, it is necessarily exotic.

Charmoniumlike mesons

Charmoniumlike XYZ mesons were first observed in 2003 and continue to be found at a rate of about one or two new ones every year. There is a huge theoretical and experimental literature on this subject that cannot be reviewed here. Instead I restrict myself to a few general remarks.

Figure 4 (left) shows the charmonium and charmoniumlike meson spectrum for masses below 4500 MeV. Here the yellow boxes indicate established charmonium states. All of the (narrow) states below the $2m_D$ open-charm threshold

have been established and found to have properties that are well described by the charmonium model. In addition all of the $J^{PC} = 1^{--}$ states above $2m_D$ have also been identified. The gray boxes show the remaining unfilled, but predicted charmonium states. The red boxes show electrically neutral X and Y mesons and the purple boxes show the charged Z mesons, aligned according to my best guess at the J^{PC} quantum numbers of their neutral charged partner. (Not included here are recently discovered resonances in the $J/\psi\phi$ channel, which are discussed in a recent review by Yi [27].) In the following, I briefly comment on each of the XYZ entries.

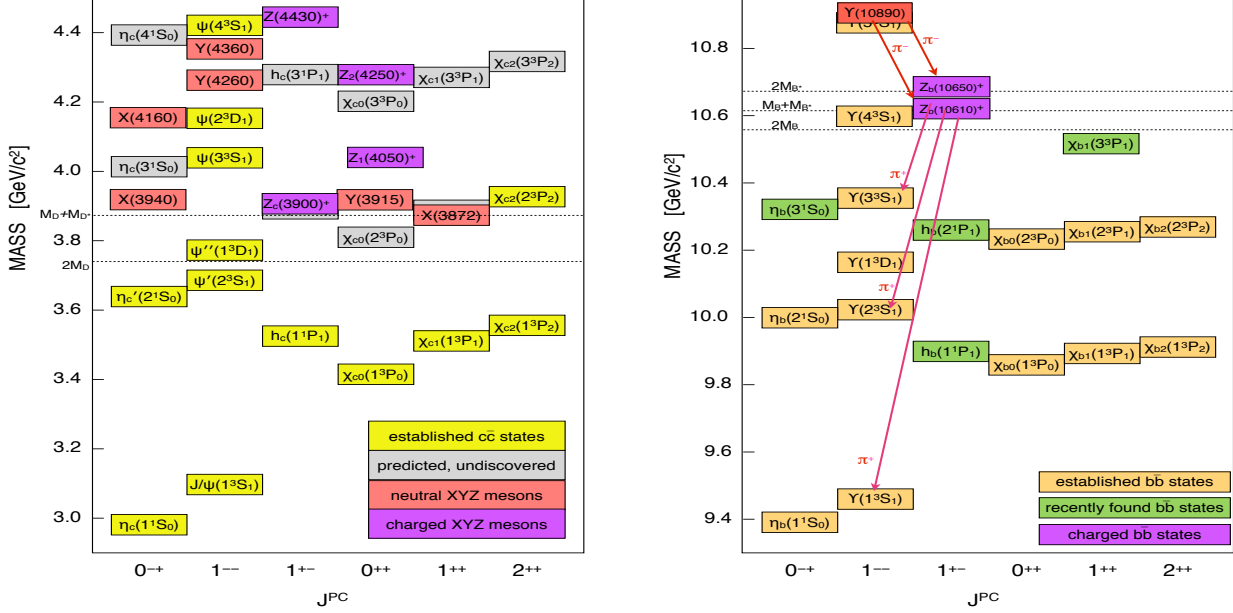


FIG. 4: The spectra of **left**) charmoniumlike and **right**) bottomoniumlike mesons.

$X(3940)$ and $X(4160)$ The $X(3940)$ and $X(4160)$ were found by Belle in the $D\bar{D}^*$ [26] and $D^*\bar{D}^*$ [28] systems recoiling against a J/ψ in $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^*$ annihilations, respectively [29]; their production mechanism and their decay modes provide strong circumstantial evidence for $J^{PC} = 0^{-+}$ assignments. In both cases, the measured masses are far below expectations for the only available 0^{-+} charmonium levels, the $\eta_c(3S)$ and $\eta_c(4S)$. These assignments would imply hyperfine $n^3S - n^1S$ mass splittings that increase from the measured value of 47.2 ± 1.2 MeV for $n = 2$ [10], to ~ 100 MeV for $n = 3$ and ~ 350 MeV for $n = 4$. This is problematic because potential models predict that hyperfine splittings decrease with increasing n .

$Y(4260)$ and $Y(4360)$ BaBar discovered the $Y(4260)$ as a peak in the $\pi^+\pi^-J/\psi$ system produced in the initial-state-radiation process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$ [30] (see the left panel of Fig. 5) and the $Y(4360)$ in the $\pi^+\pi^-\psi'$ system produced via $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi'$ [31]. These states are considered to be exotic since the production mechanism ensures that their $J^{PC} = 1^{--}$ while all of the 1^{--} $c\bar{c}$ states near their masses have already been assigned. Moreover, there is no evidence for them in any exclusive [32] or the inclusive [33] charmed meson pair production cross section, where there is a pronounced dip at $\sqrt{s} \simeq 4.26$ GeV (see the center-left panel of Fig. 5). This dip implies a large partial width for $Y(4260) \rightarrow \pi^+\pi^-J/\psi$: $\Gamma(Y(4260) \rightarrow \pi^+\pi^-J/\psi) > 1$ MeV [34], which is huge by charmonium standards.

$Z_c(3900)$, $Z_1(4050)$, $Z_2(4250)$ and $Z(4430)$ Since the $Z_c(3900)$ [35], $Z_1(4050)$ [36], $Z_2(4250)$ [36] and $Z(4430)$ [37] are electrically charged and decay to hidden charm final states, their minimal quark structure must be a $c\bar{c}u\bar{d}$ four-quark combination and they are, therefore, exotic.

$Y(3915)$ The $Y(3915)$ is an $\omega J/\psi$ mass peak at 3918 ± 3 MeV seen in $B \rightarrow K\omega J/\psi$ decays [38, 39] and in the two-photon process $\gamma\gamma \rightarrow \omega J/\psi$ [40, 41]. BaBar measured its J^{PC} quantum numbers to be 0^{++} [42]. The PDG currently assigns this as the $\chi_{c0}(2P)$ charmonium level, an assignment that has two problems: *i*) since the $\chi_{c2}(2P)$ has been established with mass 3927 ± 3 MeV, the $Y(3915) = \chi_{c0}(2P)$ assignment would imply that the $2^3P_2 - 2^3P_0$ fine splitting is only 9 ± 4 MeV, and tiny in comparison with the corresponding $n = 1$ splitting

of 141.4 ± 0.3 MeV [10]; *ii*) there is no sign of $Y(3915) \rightarrow D\bar{D}$ decay. Belle [43] and BaBar [44] have studied the process $B \rightarrow K D\bar{D}$, and both groups see a prominent signal for $\psi(3770) \rightarrow D\bar{D}$ but no hint of a $D\bar{D}$ mass peak near 3915 MeV (see the two right-most panels in Fig. 5). Since neither group reported any $Y(3915)$ -related limit, I derived my own conservative upper limit by scaling the total number of Belle events in the two mass bins surrounding 3915 MeV in the center-right panel of Fig. 5 to the $\psi(3770)$ signal, while assuming constant acceptance. This gives $\mathcal{B}(Y(3915) \rightarrow D\bar{D}) < \mathcal{B}(Y(3915) \rightarrow \omega J/\psi)$, which strongly contradicts theoretical expectations that for the $\chi_{c0}(2P)$, the $D\bar{D}$ decay channel should dominate [45]. (Note: some of the literature – and the PDG – refer to this state as the $X(3915)$.)

X(3872) The $X(3872)$ was first seen in 2003 as a peak in the $\pi^+\pi^-J/\psi$ invariant mass distribution in $B \rightarrow K\pi^+\pi^-J/\psi$ decays [46]. Its mass is indistinguishable from the $m_{D^0} + m_{D^{*0}}$ threshold; the most recent result from LHCb is $M_{X(3872)} - (m_{D^0} + m_{D^{*0}}) = -0.09 \pm 0.28$ MeV [47]. LHCb also established the J^{PC} quantum numbers as 1^{++} [48]. The $X(3872)$ has a long interesting story that I will not attempt to even summarize in this brief report. Instead I refer the reader to ref. [49] and references cited therein.

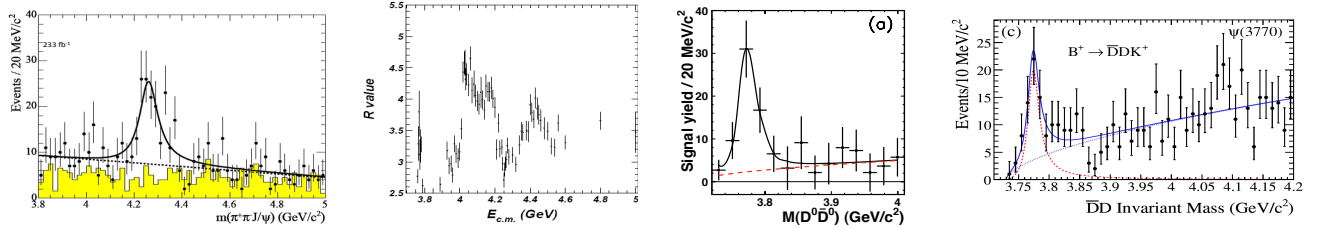


FIG. 5: **Left)** The $M(\pi^+\pi^-J/\psi)$ distribution from $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ process near $\sqrt{s} = 10.6$ GeV from ref. [30]. **Center-left)** Inclusive Born cross section for e^+e^- annihilation into hadrons from ref. [33]. **Center-right)** The $M(D^0\bar{D}^0)$ distribution from $B \rightarrow K D^0\bar{D}^0$ decays from Belle [43]. **Right)** The $M(D\bar{D})$ distribution from $B \rightarrow K D\bar{D}$ decays from BaBar [44].

Bottomoniumlike mesons

The right panel of Fig. 4 shows the recent status of the $b\bar{b}$ bottomonium and bottomoniumlike mesons. Here the orange boxes indicate the well established bottomonium mesons and the green boxes show those that were recently established. The large $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ signal seen in the charmonium mass region motivated a Belle search for similar behavior in the bottomonium system [50] that uncovered an anomalously large $\pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$) production rates that peak around $\sqrt{s} = 10.89$ GeV as shown in the upper-left panel of Fig. 6 [51]. The peak position of the $\pi^+\pi^-\Upsilon(nS)$ yield is about 2σ higher than that of the peak in the $e^+e^- \rightarrow \text{hadron}$ cross section at $\sqrt{s} \simeq 10.87$ GeV that is usually associated with the conventional $\Upsilon(5S)$ $b\bar{b}$ meson (and shown in the lower left panel of Fig. 6). If the peak in the $\pi^+\pi^-\Upsilon(nS)$ cross section is attributed to the $\Upsilon(5S)$, it implies $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$, ($n = 1, 2, 3$) partial widths that are hundreds of times larger than both theoretical predictions [52] and the corresponding measured values for the $\Upsilon(4S)$ [10]). This suggests the presence of a $b\bar{b}$ equivalent of the $Y(4260)$ with mass near 10,890 MeV, as suggested in ref. [50].

The upper right panel of Fig. 6 shows the distribution of masses recoiling against all of the $\pi^+\pi^-$ pairs in events collected at near $\sqrt{s} \simeq 10.87$ GeV, near the peak of the $\Upsilon(5S)$ resonance. The combinatoric background is huge – there are typically 10^6 entries in each 1 MeV bin – and the statistical errors are $\sim 0.1\%$. The data were fit piece-wise with sixth-order polynomials, and the residuals from the fits are shown in the lower right panel of Fig. 6, where, in addition to peaks at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and some expected reflections, there are unambiguous signals for the $h_b(1P)$ and $h_b(2P)$, the 1^1P_1 and 2^1P_1 bottomonium states. This was the first observation of these two elusive levels [53]. One puzzle is that the $\pi^+\pi^-h_b(mS)$, ($m = 1, 2$) final states are produced at rates that are nearly the same as those for $\pi^+\pi^-\Upsilon(nS)$, ($n = 1, 2, 3$), even though the $\pi^+\pi^-h_b$ transition requires a heavy-quark spin flip, which should result in a strong suppression. This motivated a more detailed investigation of these channels.

The left panels of Fig. 7 show the $\pi^+\pi^-h_b$ yield versus the maximum $h_b\pi^\pm$ invariant mass for $h_b = h_b(1P)$ (upper) and $h_b = h_b(2P)$ (lower), where it can be seen that all of the $\pi^+\pi^-h_b$ events are concentrated in two $M_{\text{max}}(h_b\pi)$ peaks, one near 10,610 MeV and the other near 10,650 MeV [54]. Studies of fully reconstructed $\pi^+\pi^-\Upsilon(nS)$, ($n = 1, 2, 3$), $\Upsilon(nS) \rightarrow \ell^+\ell^-$ events in the same data sample show two peaks in the $M_{\text{max}}(\Upsilon(nS)\pi)$ distributions at the same masses

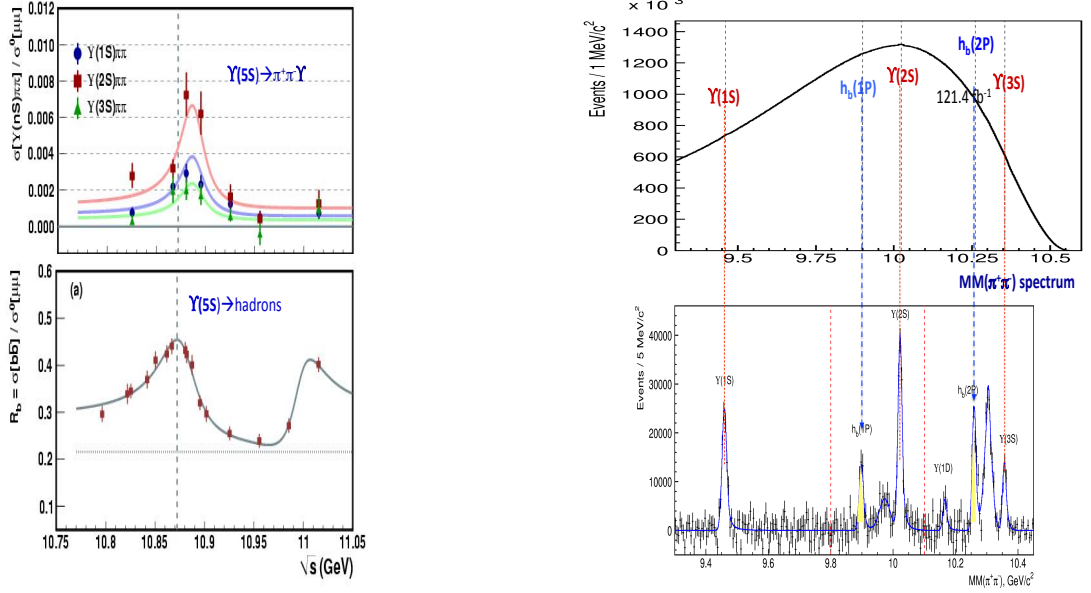


FIG. 6: **Left**) Cross sections for $e^+e^- \rightarrow \pi^+\pi^-Y(nS)$ ($n = 1, 2, 3$) (upper) and $e^+e^- \rightarrow \text{hadrons}$ ((lower) in the vicinity of the $Y(5S)$ resonance from ref. [51]. **Right**) Distribution of masses recoiling against $\pi^+\pi^-$ pairs at $\sqrt{s} \simeq 10.87$ GeV (upper) and residuals from piecewise fits to the data with smooth polynomials (lower) (from ref. [53]). The $h_b(1P)$ and $h_b(2P)$ peaks are shaded in yellow.

for all three modes, as shown in the three center panels of Fig. 7. Here the fractions of $\pi^+\pi^-Y(nS)$ events in the two peaks are substantial – $\sim 6\%$ for the $Y(1S)$, $\sim 22\%$ for the $Y(2S)$ and $\sim 43\%$ for the $Y(3S)$ – but do not account for all of the $\pi^+\pi^-Y(nS)$ event yield [55]. The peak masses and widths in all five channels are consistent with each other and the weighted average mass and width values are $M_{Z_b(10610)} = 10607.2 \pm 2.0$ MeV & $\Gamma_{Z_b(10610)} = 18.4 \pm 2.4$ MeV, and $M_{Z_b(10650)} = 10652.2 \pm 1.5$ MeV & $\Gamma_{Z_b(10650)} = 11.5 \pm 2.2$ MeV. Dalitz-plot analyses of the $\pi^+\pi^-Y(nS)$ final states establish $J^P = 1^+$ quantum number assignments for both states. The lower mass state is just 2.6 ± 2.2 MeV above the $m_B + m_{B^*}$ mass threshold and the higher mass state is only 2.0 ± 1.6 MeV above $2m_{B^*}$, which, together with the $J^P = 1^+$ assignment, is suggestive of virtual $B\bar{B}^*$ and $B^*\bar{B}^*$ S -wave molecule-like states.

The $B^{(*)}\bar{B}^*$ molecule picture is supported by a Belle study of $e^+e^- \rightarrow B^{(*)}\bar{B}^*\pi$ final states in the same data sample [56], where $B\bar{B}^*$ and $B^*\bar{B}^*$ invariant mass peaks are seen at the $Z_b(10610)$ and $Z_b(10650)$ mass values, respectively, as shown in the right panels of Fig. 7. From these data, preliminary values of the branching fractions $\mathcal{B}(Z_b(10610)^+ \rightarrow B^+\bar{B}^{*0} + \bar{B}^0B^{*+} + c.c.) = (86.0 \pm 3.6)\%$ and $\mathcal{B}(Z_b(10610)^+ \rightarrow B^{*+}\bar{B}^{*0} + c.c.) = (73.4 \pm 7.0)\%$ are inferred. The measured branching fraction for $Z_b(10610) \rightarrow B^*\bar{B}^*$ is consistent with zero. This pattern, where $B\bar{B}^*$ decays dominate for the $Z_b(10610)$ and $B^*\bar{B}^*$ decays are dominant for the $Z_b(10650)$ are consistent with expectations for molecule-like structures.

Operating BESIII/BEPCII as a $Y(4260)$ factory

As described above, the peculiar properties of the $Y(4260)$ charmoniumlike state motivated the Belle studies of the $\pi^+\pi^-Y(nS)$ and $\pi^+\pi^-h_b(mP)$ channels at energies near the peak of the $Y(5S)$ and led to the discovery of the charged, bottomoniumlike Z_b mesons. These discoveries, in turn, inspired the BESIII group to revisit the $Y(4260)$ by operating the Beijing Electron-Positron Collider (BEPCII) at $\sqrt{s} = 4.26$ GeV, and accumulating a large sample of $Y(4260)$ decay events.

The first channel to be studied with these data was the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$, where a distinct peak in the distribution of the larger of the two $J/\psi\pi^\pm$ invariant mass combinations in each event ($M_{\max}(J/\psi\pi)$), exhibits a distinct peak near $M_{\max}(J/\psi\pi) \simeq 3900$ MeV, which is called the $Z_c(3900)$ and shown in the left panel of Fig. 8 [35]. A fit using a mass-independent-width BW function to represent the peak yielded a mass and width of $M_{Z_c(3900)} = 3899.0 \pm 6.1$ MeV and $\Gamma_{Z_c(3900)} = 46 \pm 22$ MeV, which is ~ 20 MeV above the $m_D + m_{D^*}$ threshold. The $Z_c(3900)$, which looks like a charmed-sector version of the $Z_b(10610)$, was subsequently confirmed by Belle [57].

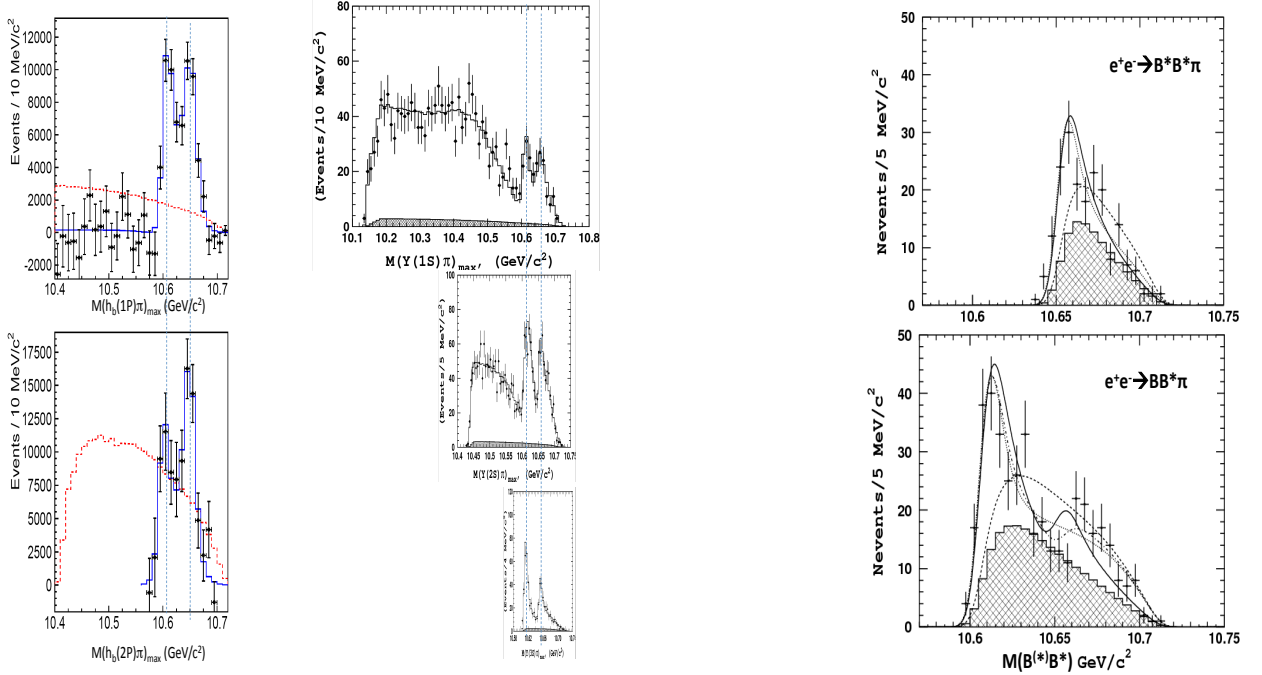


FIG. 7: **Left)** invariant mass distributions for $h_b(1P)\pi^+$ (upper) and $h_b(2P)\pi^+$ (lower) from $e^+e^- \rightarrow \pi^+\pi^-h_b(nP)$ events. **Center)** Invariant mass distributions for $\Upsilon(1S)\pi^+$ (upper), $\Upsilon(2S)\pi^+$ (center) and $\Upsilon(3S)\pi^+$ (lower) in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$ events. the figures are from ref. [54], and scaled to make the horizontal scales (almost) match. **Right)** The $M(B^*B^*)$ (upper) and $M(BB^*)$ (lower) invariant mass distributions from $e^+e^- \rightarrow B^{(*)}\bar{B}^*\pi$ events near $\sqrt{s} = 10.97$ GeV (from ref. [56]).

The close proximity of the $Z_c(3900)$ mass to the $m_D + m_{D^*}$ threshold motivated a BESIII study of the $(D\bar{D}^*)^+$ systems produced in $(D\bar{D}^*)^\pm\pi^\mp$ final states in the same data sample [58]. There, dramatic near-threshold peaks are seen in both the D^0D^{*-} and $D^+\bar{D}^{*0}$ invariant mass distributions; as an example, the $M(D^0D^{*-})$ distribution is shown in the center-left panel of Fig. 8. The weighted average mass and width from fits of a threshold-modified BW line shapes to these distributions gives resonance pole position $(M_{\text{pole}} + i\Gamma_{\text{pole}})$ values of $M_{\text{pole}} = 3883.9 \pm 4.5$ MeV and $\Gamma_{\text{pole}} = 24.8 \pm 12$ MeV. For these data, the production angle dependence strongly favors a $J^P = 1^+$ quantum number assignment and decisively rules out $J^P = 0^-$ and 1^- (0^+ is ruled out by parity conservation). Since the pole mass position is $\simeq 2\sigma$ lower than the $Z_c(3900)$ mass, BESIII tentatively named this $D\bar{D}^*$ state the $Z_c(3885)$. In the mass determinations of both the $Z_c(3885)$ and $Z_c(3900)$, effects of possible interference with a coherent component of the background are ignored. Since this can bias the measurements by amounts comparable to the resonance widths, which are large, this may account for the discrepancy in masses. A partial wave analysis of the $\pi^+\pi^-J/\psi$ channel, which is currently underway, may establish the J^P quantum numbers of the $Z_c(3900)$ and provide important input into the question of whether or not these are the same state. If the $Z_c(3885)$ and the $Z_c(3900)$ are in fact the same, the partial width for $D\bar{D}^*$ decays is 6.2 ± 2.9 times larger than that for $J/\psi\pi$. This is small compared to open-charm versus hidden-charm decay-width ratios for established charmonium states that are above the open-charm threshold, such as the $\psi(3770)$ and $\psi(4040)$, where corresponding ratios are measured to be more than an order-of-magnitude larger [10].

A study of $\pi^+\pi^-h_c(1P)$ final states in data taken at $\sqrt{s} = 4.26$ GeV and nearby energy points uncovered the sharp peak in the $M_{\text{max}}(h_c\pi^\pm)$ distribution near 4020 MeV that is shown in the center-right panel of Fig. 8. This peak, called the $Z_c(4020)$, has a fitted mass of $M_{Z_c(4020)} = 4022.9 \pm 1.8$ MeV, which is only ~ 6 MeV above $2m_{D^*}$, and a width of $\Gamma_{Z_c(4020)} = 7.9 \pm 3.8$ MeV [60]. This state looks like a charmed-sector version of the $Z_b(10650)$.

A study of $e^+e^- \rightarrow D^*\bar{D}^*\pi^\pm$ events in the $\sqrt{s} = 4.26$ GeV data sample produced the $M(D^*\bar{D}^*)$ invariant mass distribution shown in the right panel of Fig. 8. Here the limited available phase space limits the ability to see a distinct peak above background. However, the distribution cannot be explained by a phase-space term (dash-dot curve) plus background (dotted curve). The best fit includes a a BW term with peak mass near 4025 MeV, dubbed the $Z_c(4025)$ [59]. Here a fit using a mass-independent-width BW line shape function modified by a phase space factor that accounts for the nearby $2m_{D^*}$ mass threshold yields a mass $M_{Z_c(4025)} = 4026.3 \pm 4.5$ MeV, which is ~ 10 MeV

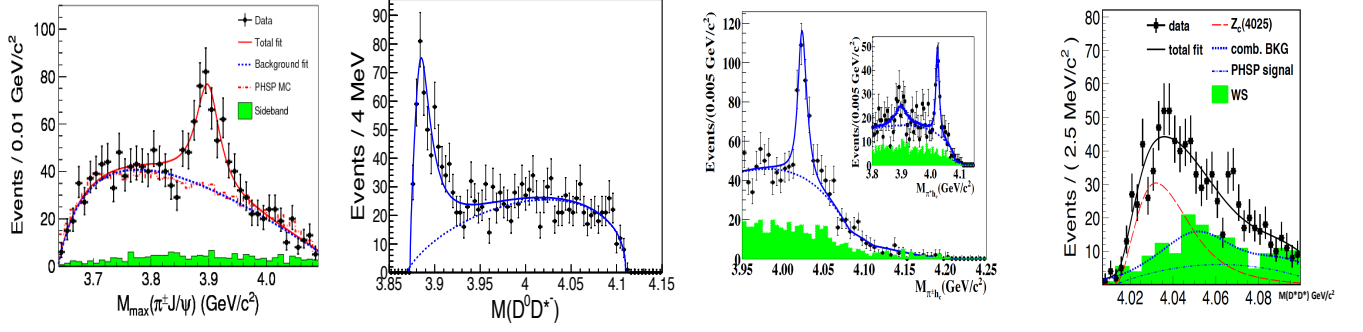


FIG. 8: Invariant mass distributions for $J/\psi\pi^+$ from $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ events (**Left**), $D\bar{D}^*$ from $e^+e^- \rightarrow (D\bar{D}^*)^+\pi^-$ events (**Center-left**), $h_c(1P)\pi^+$ from $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$ events (**Center-right**) near $\sqrt{s} = 4.26$ GeV and $D^*\bar{D}^*$ from $e^+e^- \rightarrow (D^*\bar{D}^*)^+\pi^-$ events (**Right**) at $\sqrt{s} = 4.26$ GeV.

above the $2m_{D^*}$ threshold, and a width $\Gamma_{Z_c(4025)} = 24.5 \pm 9.5$ MeV. The mass of the $Z_c(4025)$ is consistent within errors with the mass of the $Z_c(4020)$, but its width is about 2σ higher. Width measurements could be effected by interference with a coherent background so, although it seems likely that the $Z_c(4020)$ and $Z_c(4025)$ are different decay channels of the same state, more studies are needed before a firm conclusion can be drawn.

Comments

The recent BESIII findings, taken together with previous experimental results, establishes a concentration of charmoniumlike states crowding the $D\bar{D}^*$ and $D^*\bar{D}^*$ mass threshold regions. There are at least four states very close the $D\bar{D}^*$ threshold. The $X(3872)$ is right at the $D^0 + D^{*0}$ threshold and seems to be an isospin singlet [61]. The $Z_c(3885)$ pole mass is about 10 MeV above the $D^0 D^{*-}$ or $D^+ \bar{D}^{*0}$ threshold and is an isospin triplet. Both have $J^P = 1^+$ and couple to S -wave $D\bar{D}^*$ final states. The $Z_c(4020)/Z_c(4025)$ states show the existence of at least one isospin triplet just above the $D^* \bar{D}^*$ threshold. If this is the charmed-sector equivalent of the $Z_b(10650)$, then it has $J^P = 1^+$, in which case there is, at present, no obvious candidate for a isospin-singlet counterpart. If such a state exists with a mass that is above the $2m_{D^*}$ threshold and with a relatively narrow width, it might be accessible in $B^- \rightarrow K^- D^* \bar{D}^*$ decays. BaBar has reported large branching fractions for $B^- \rightarrow K^- D^{*0} \bar{D}^{*0}$ ($1.1 \pm 0.1\%$) and $K^- D^{*+} D^{*-}$ ($0.13 \pm 0.02\%$) but did not publish any invariant mass distributions [62].

The CMS group searched for a b -quark-sector equivalent of the $X(3872)$ in the inclusive $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution produced in in proton-proton collisions at $\sqrt{s} = 8$ TeV, but found no evidence for peaks other than those due to $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\pi^+\pi^-\Upsilon(1S)$ transitions [63]. However, if, as expected, the b -quark-sector equivalent of the $X(3872)$ has $J^{PC} = 1^{++}$, zero isospin, and is near the $B\bar{B}^*$ mass threshold, the $\pi^+\pi^-\Upsilon(1S)$ decay mode, for which the $\pi^+\pi^-$ would originate from $\rho \rightarrow \pi^+\pi^-$, would violate isospin and be strongly suppressed relative to decays to the isospin-conserving $\omega\Upsilon(1S)$ final state. (This is not the case for the $X(3872)$ where the isospin-allowed $\omega J/\psi$ decay mode is kinematically suppressed: i.e., $Q_c \simeq m_{D^0} + m_{D^{*0}} - m_{J/\psi} = 776$ MeV, which is twice the ω natural width below its peak mass $m_\omega = 783$ MeV. In the b -quark-sector, $m_B + m_{B^*} - m_{\Upsilon(1S)} = 1145$ MeV, which is well above m_ω .) Thus, $\omega\Upsilon(1S)$ final states are probably more relevant than $\pi^+\pi^-\Upsilon(1S)$ for searches for isospin-singlet counterparts of the $Z_b(10610)$ and $Z_b(10650)$. This would require studies of decay final states that contain a π^0 , which will may be difficult to do with existing experiments, but could be done at BelleII [64].

SUMMARY

The QCD exotic states that are much preferred by theorists, such as pentaquarks, the H -dibaryon, and meson hybrids with exotic J^{PC} values continue to elude confirmation even in experiments with increasingly high levels of sensitivity. On the other hand, a candidate $p\bar{p}$ bound state and a rich spectroscopy of quarkoniumlike states that do not fit into the remaining unassigned levels for $c\bar{c}$ charmonium and $b\bar{b}$ bottomonium states has emerged. No compelling theoretical picture has yet been found that provides a compelling description of what is seen, but, since at least some of these states are near $D^{(*)}\bar{D}^*$ or $B^{(*)}\bar{B}^*$ thresholds and couple to S -wave combinations of these states,

molecule-like configurations have to be important components of their wavefunctions [65]. This has inspired a new field of “flavor chemistry” that is attracting considerable attention both by the experimental and theoretical hadron physics communities [66].

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